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DESIGN, FABRICATION AND TEST OF A FLUERIC SERVOVALVE

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Quarterly Report

DESIGN, FABRICATION AND TEST OF A FLUERIC SERVOVALVE

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ABSTRACT

Development tests were performed on a breadboard model of a pneumatic-input fluoric servovalve, which operates with no moving parts. The servovalve is designed to operate with H_2 at temperatures from 56°K (100°R) to 333°K (600°R), supply pressure of 148 N/cm² (215 psia), exhaust pressure of 34.5 N/cm² (50 psia), and maximum control pressure of 48.5 N/cm² (70.4 psia). Tests were performed on the power stage vortex pressure amplifier to improve the stability. As an alternative to the vortex pressure amplifier, a vortex bridge type of power stage was also tested. All tests for this period were performed using nitrogen. This report presents the results of tests performed during the fourth three-month period of the program.

AUTHOR

SECTION 1

INTRODUCTION

The objective of this program is to develop a high-performance, pneumatic-input, four-way flueric servovalve with dynamic load pressure feedback. A flueric servovalve has no moving parts and therefore offers advantages in reliability and maintenance, particularly when it must operate in severe environments of nuclear radiation, temperature, shock or vibration.

Earlier flueric servovalve development efforts were presented in NASA Report CR-54463, entitled "Design, Fabrication, and Test of a Fluid Interaction Servovalve." As an advancement stemming from that earlier development, the servovalve described in this report achieves higher performance by incorporating a more stable type of power stage, a jet-on-jet proportional amplifier in the pilot stage, and dynamic pressure feedback.

This development effort is divided into two phases. In Phase I, a breadboard model of the servovalve has been designed and fabricated and is being tested at room temperature. The design procedure and component tests were presented in NASA Reports CR-54783, CR-54901, and CR-72023, all entitled "Design, Fabrication, and Test of a Flueric Servovalve." In Phase II, a prototype servovalve will be designed to fit a flueric position servo for the control drum of a nuclear rocket. This report covers the fourth calendar quarter of Phase I.

The results of this fourth-quarter effort are summarized in Section 2. Section 3 describes the function of the various servovalve components. The results of development tests of the power stage are described in Sections 4 and 5. Goals for the next quarter are listed in Section 6, and the specifications of the breadboard servovalve are presented in Appendix A.

SECTION 2

SUMMARY

The servovalve consists of a pilot stage and a power stage. The power stage consists of four vortex valves in a bridge circuit. The pilot stage is made up of a jet-on-jet proportional amplifier, two Venjet amplifiers, two summing vortex valves and an ejector. The jet-on-jet proportional amplifier provides the push-pull control signals to the power stage. The output of each Venjet amplifier is the control signal to one side or the other of the jet-on-jet proportional amplifier. The Venjet amplifier enables a high output pressure to be controlled by a low vent pressure, which in turn is controlled by a summing vortex valve. The summing vortex valves are controlled primarily by the servovalve input signal, but they also have load pressure feedback inputs.

2.1 STATUS AT BEGINNING OF FOURTH QUARTER

In the previous quarterly periods, the breadboard servovalve was designed, detail drawings were prepared, and the servovalve parts were manufactured. Developmental tests of the pilot stage and power stage components were conducted. Component geometry and sizes that must be established through actual testing to achieve the desired performance were obtained from room temperature tests using nitrogen as the working fluid. A Venjet amplifier and a power stage vortex pressure amplifier also were tested with room temperature hydrogen. It was found that the performance characteristics of these components were almost the same with hydrogen as with nitrogen.

An oscillation was found in the output pressure of the power stage vortex pressure amplifiers. The oscillation was found to be caused by a negative resistance region in the output pressure-flow characteristics. An evaluation test was conducted on the servovalve in order to determine how well the complete servovalve would perform and what interface problems might exist between the components of the servovalve. The linearity, flow recovery, pressure recovery and input-signal power were measured, first using nitrogen as the gaseous medium and then using hydrogen. Other performance items were measured using nitrogen only. It was shown that the servovalve will operate on either

hydrogen or nitrogen with minor differences in performance. The servovalve performance was good in several areas including frequency response and flow recovery. Deficiencies in performance were found in stability, linearity, and pressure recovery. The source of the servovalve instability was found to be in the power stage.

2.2 ACCOMPLISHMENTS DURING FOURTH QUARTER

In this period, development tests were performed on the power stage vortex pressure amplifier to improve the stability. As a backup alternative to the vortex pressure amplifier, a vortex bridge type of power stage was also tested.

It had been found in previous tests that the instability of the vortex pressure amplifiers was due to a negative resistance region in the receiver pressure-flow characteristics. Numerous changes were made in the probe receiver entrance and vortex chamber exit orifice in an effort to eliminate the negative resistance region. The stability of the vortex pressure amplifier was improved slightly as a result of these tests but the oscillation due to negative resistance was not eliminated. The vortex amplifier tests are described in Section 4.

The vortex valve bridge power stage (described in detail in Section 5.1) consists of four vortex valves in a bridge circuit. This vortex valve bridge power stage requires more control flow than the vortex pressure amplifier power stage. A preliminary breadboard circuit representing one side was assembled from existing vortex valves and tested. It was found that this circuit has stable, quiet output pressure characteristics. The pressure recovery was slightly low because the orifice sizes had not been optimized. A complete vortex valve bridge power stage was then built and tested. The pressure recovery was about equal to that of the vortex pressure amplifier power stage, but the output pressure was slightly oscillatory. It should be possible to achieve stable and quiet output pressure characteristics comparable to that found in tests of the preliminary breadboard circuit by proper sizing of the control and vortex chamber exit orifices.

On the basis of the test results of both types of power stages, it was decided to use the vortex valve bridge power stage because preliminary test data indicate that it should have superior stability characteristics. Since the vortex valve bridge power stage requires more control flow, it is necessary to improve the pilot stage flow recovery.

This is accomplished by incorporating a jet-on-jet proportional amplifier in the pilot stage. A test was performed on the vortex valve bridge controlled by a jet-on-jet proportional amplifier pilot stage. It was found that the jet-on-jet proportional amplifier had adequate pressure recovery, flow recovery and stability.

2.3 FIFTH-QUARTER OBJECTIVES

Goals for the next period include improving the stability of the vortex valve bridge and testing the servovalve with the addition of the Venjet amplifiers and summing vortex valves. The breadboard servovalve will then be acceptance-tested, and the design of the prototype servovalve will be initiated.

SECTION 3

DESCRIPTION OF SERVOVALVE

The flueric servovalve is a pneumatic input, four-way, "open centered" valve consisting of a pilot stage and power stage. Several changes have been made in the servovalve circuit in the past quarter. The previous servovalve configuration is shown in Figure 3-1. The power stage consisted of two vortex pressure amplifiers. The pilot stage consisted of two Venjet pressure amplifiers, two summing vortex valves, and two vortex pressure amplifiers which are used to provide regenerative feedback.

A schematic of the new servovalve configuration is shown in Figure 3-2. The power stage is made up of four vortex valves connected in a bridge type circuit. This circuit was found to be more stable than the vortex pressure amplifier power stage. An explanation of the power stage operation is given in Section 5.1.

In the pilot stage circuit, a jet-on-jet proportional amplifier and ejector have been added and the regenerative feedback vortex pressure amplifiers have been removed. The jet-on-jet proportional amplifier increases the pilot stage flow recovery because the exhaust flow of the jet-on-jet proportional amplifier is used as part of the supply flow to the power stage. The regenerative feedback is no longer included because the jet-on-jet provides the additional power gain which was previously provided by the regenerative feedback.

The pilot stage consists of a jet-on-jet proportional amplifier, an ejector, two Venjet amplifiers and two summing vortex valves. The jet-on-jet proportional amplifier provides the push-pull control signals to the supply vortex valves of the power stage. The exhaust flow from the jet-on-jet proportional amplifier is used as part of the supply flow to the power stage, which increases the servovalve flow recovery.

The exhaust pressure of the jet-on-jet proportional amplifier must be slightly lower than the power stage supply pressure. The reason for this is as follows: The minimum control pressure to the supply vortex valves of the power stage must be slightly below the supply pressure in order to achieve the zero control flow condition because there

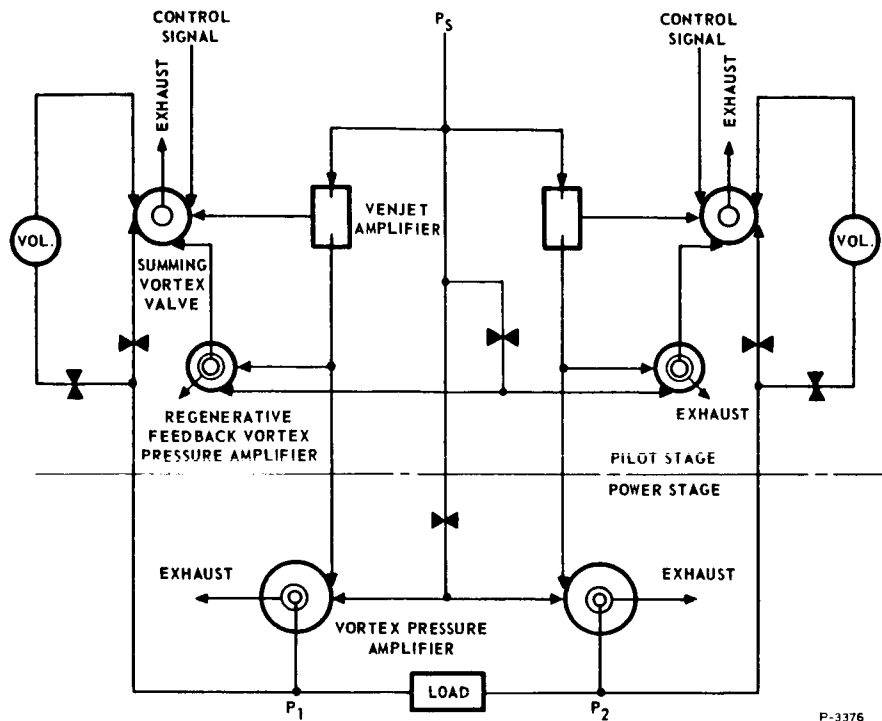


Figure 3-1 - Schematic of Flueric Servovalve with Vortex Pressure Amplifier Power Stage

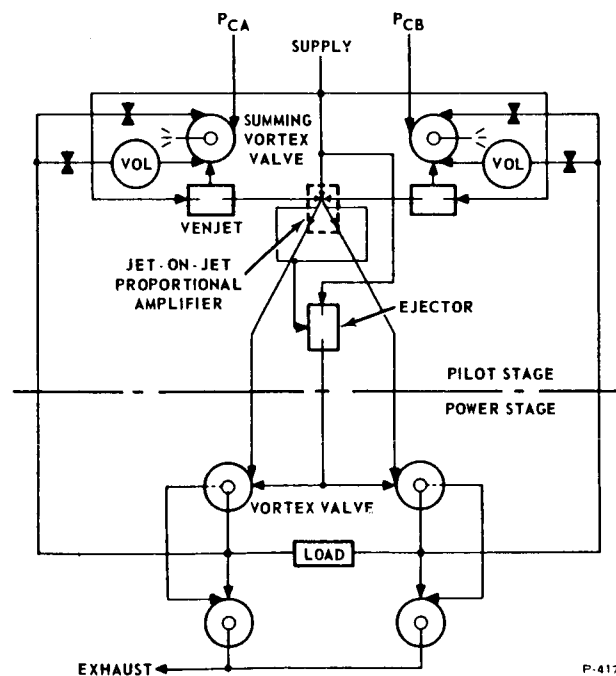


Figure 3-2 - Schematic of Flueric Servovalve with Vortex Valve Bridge Power Stage and with Jet-on-Jet Proportional Amplifier in Pilot Stage

is a slight pressure drop from the power stage supply line to the vortex chambers of the supply vortex valves. However, the output pressure of the jet-on-jet proportional amplifier will not go below its exhaust pressure. Therefore, to make the minimum output pressure low enough, it is necessary to keep the exhaust pressure of the jet-on-jet amplifier slightly lower than the power stage supply pressure. After the exhaust flow leaves the jet-on-jet amplifier, the ejector acts as a pump to boost the exhaust flow pressure by 1.4 to 2.8 N/cm² (2 to 4 psi) to bring it up to the power stage supply pressure level.

The outputs of the Venjet amplifiers are connected to the control ports of the jet-on-jet proportional amplifier. The control pressure level of the jet-on-jet proportional amplifier must be equal to or higher than its exhaust pressure which is about 120 N/cm² (175 psia). The input signal pressure bias to the servovalve is about 45 N/cm² (65.3 psia). The Venjet amplifier enables a high output pressure to be controlled by a low vent pressure, which in turn is controlled by a summing vortex valve.

The primary control flow to each summing vortex valve is one of the servovalve input signals. The summing vortex valve also contains two opposing control ports which are connected to the load volume and which receive the load pressure feedback signal.

SECTION 4

VORTEX AMPLIFIER TESTS

Developmental tests were conducted during the fourth-quarter period with the objective of improving the stability of the power stage vortex pressure amplifiers used in the original servovalve circuit. It had been found in previous tests that the instability of the vortex pressure amplifiers was due to a negative resistance region in the receiver pressure-flow characteristics. Changes were made in the probe receiver entrance and vortex chamber exit orifice in an effort to eliminate the negative resistance region. A receiver configuration was found in which the negative resistance was eliminated in a single-exit amplifier. However, negative resistance was still found to be present in the dual-exit pressure amplifier. Further analysis and testing would be necessary to develop a stable power stage vortex pressure amplifier.

4.1 TEST PROCEDURE

Since the vortex amplifiers operate in push-pull, flow is positive in one amplifier (outward through the receiver toward the load) while reverse flow occurs at the other amplifier (inward through the receiver). Thus, flow in both the positive and reverse directions is of interest. The primary cause of the power stage instability was found to be a negative resistance region in the pressure-flow characteristics of the receiver. Therefore, the changes in geometry of the receiver and vortex chamber exit were evaluated by plotting the receiver output flow versus the output pressure. In most of the tests, only the reverse flow direction was plotted because it was found in earlier tests that the negative resistance region was located primarily in the reverse output flow quadrant, although the negative resistance region did cross over the zero flow axis into the positive output flow direction.

Data were taken at several constant control pressure levels in order to obtain a family of curves. A schematic of the test setup is shown in Figure 4-1. A schematic of the power stage vortex pressure amplifier is shown in Figure 4-2. The vortex pressure amplifier used for the servovalve power stage is a dual-exit type with an exit orifice and receiver on each side of the vortex chamber. For most of the tests,

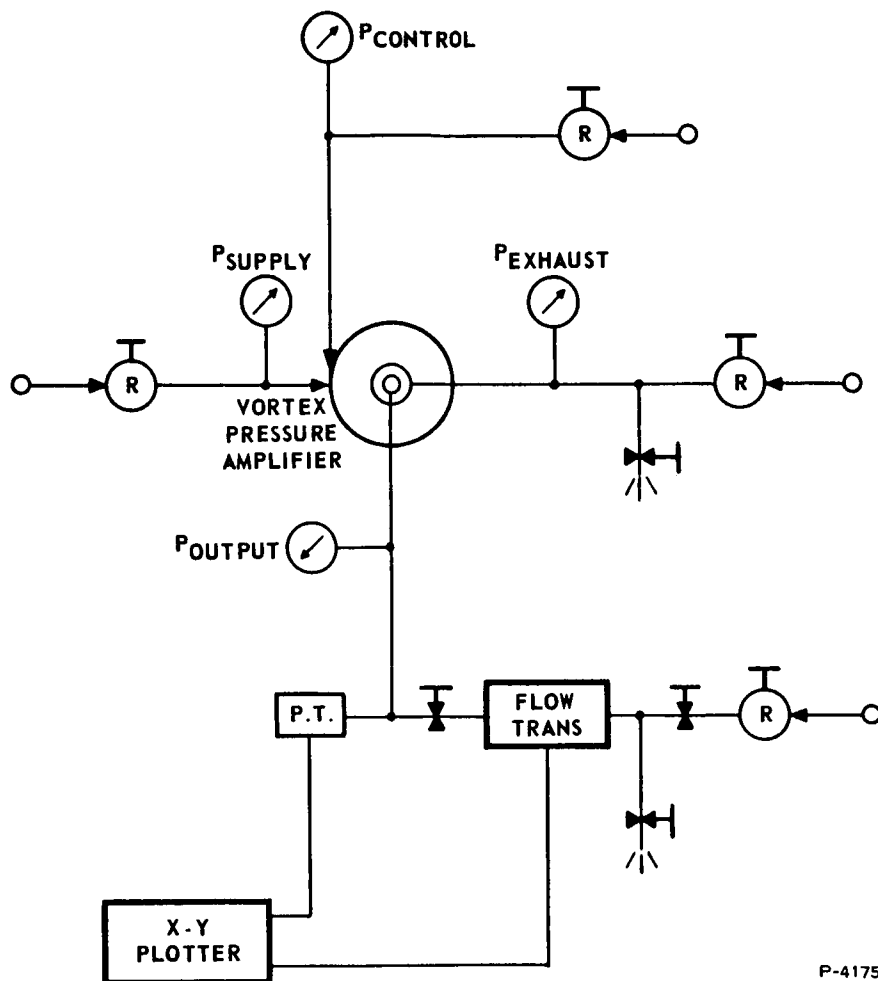


Figure 4-1 - Schematic of Vortex Pressure Amplifier Test Setup

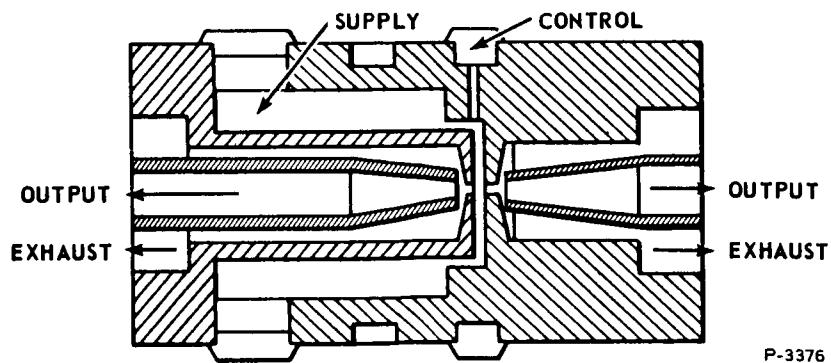


Figure 4-2 - Dual-Exit Vortex Pressure Amplifier

the exit orifice and receiver were blocked off on one side of the vortex chamber. The significant dimensions of the vortex pressure amplifier are as follows:

Vortex Chamber Diameter	1.112 cm (0.438 in.)
Vortex Chamber Length	0.094 cm (0.037 in.)
Button Diameter	1.062 cm (0.418 in.)
Exit Orifice Diameter (two orifices)	0.094 cm (0.037 in.)
Control Orifice Diameter (four orifices)	0.046 cm (0.018 in.)
Receiver Diameter	0.104 cm (0.041 in.)
Distance Between Exit Orifice and Receiver	0.028 cm (0.011 in.)

4.2 TEST RESULTS

The receiver pressure-flow characteristics of one side of the vortex pressure amplifier before any changes were made are shown in Figure 4-3. Negative resistance is seen in the $P_c = 122.8 \text{ N/cm}^2$ and $P_c = 123.1 \text{ N/cm}^2$ curves.

Several changes were made to the receiver face in an effort to eliminate the negative resistance. Figure 4-4 shows the pressure-flow characteristics for a flat-faced type of receiver. The negative resistance has been eliminated in this case but the maximum output pressure is low under the blocked output condition. The maximum blocked output pressure is 8 percent lower than that originally obtained. Figure 4-5 shows the effect of chamfering the receiver orifice entrance. Here again, no negative resistance is seen but the maximum recovered pressure is even lower than before. Figure 4-6 shows the pressure-flow characteristics of a receiver with a tapered outside edge and only a very small flat at the tip. The pressure-flow characteristics for this case are about the same as for the flat-faced receiver shown in Figure 4-4.

The geometry around the vortex chamber exit orifice was also changed in an effort to improve the pressure recovery. The area around the exit orifice was undercut as shown in Figure 4-7. A flat-faced receiver was used with the undercut exit orifice. In Figure 4-7, it is

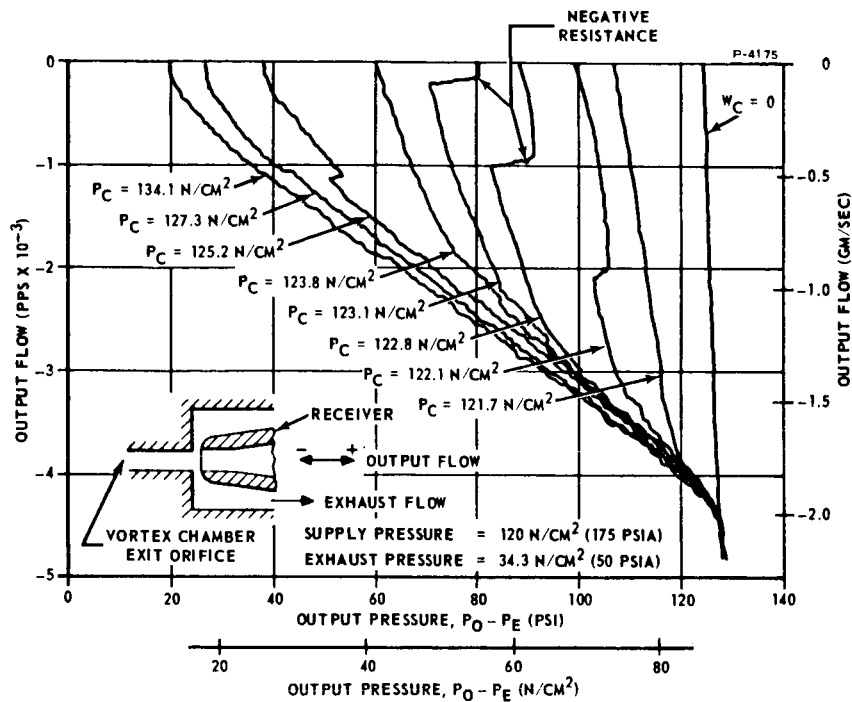


Figure 4-3 - Receiver Pressure - Flow Characteristics of Vortex Pressure Amplifier (Original Configuration)

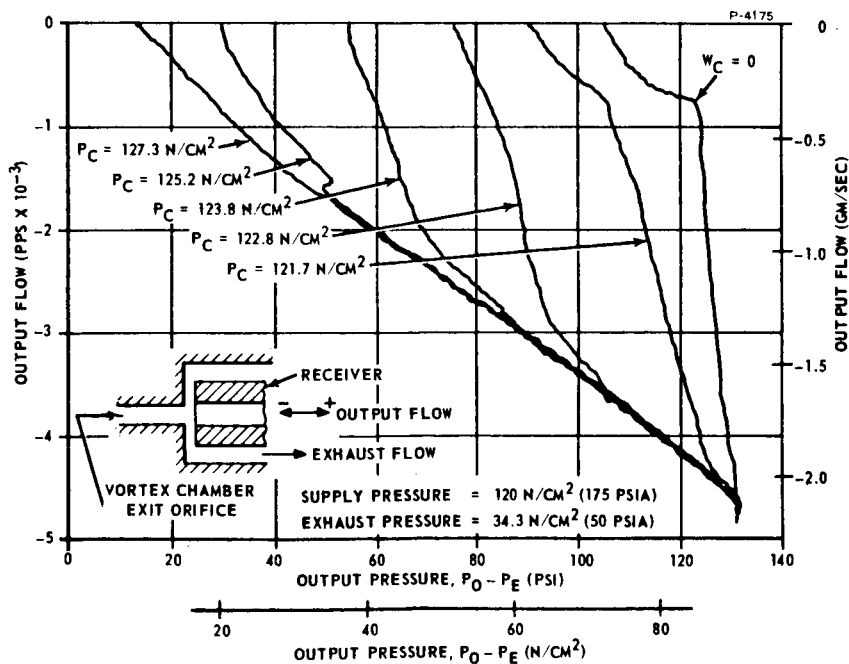


Figure 4-4 - Receiver Pressure - Flow Characteristics of Vortex Pressure Amplifier (Flat Faced Receiver Configuration)

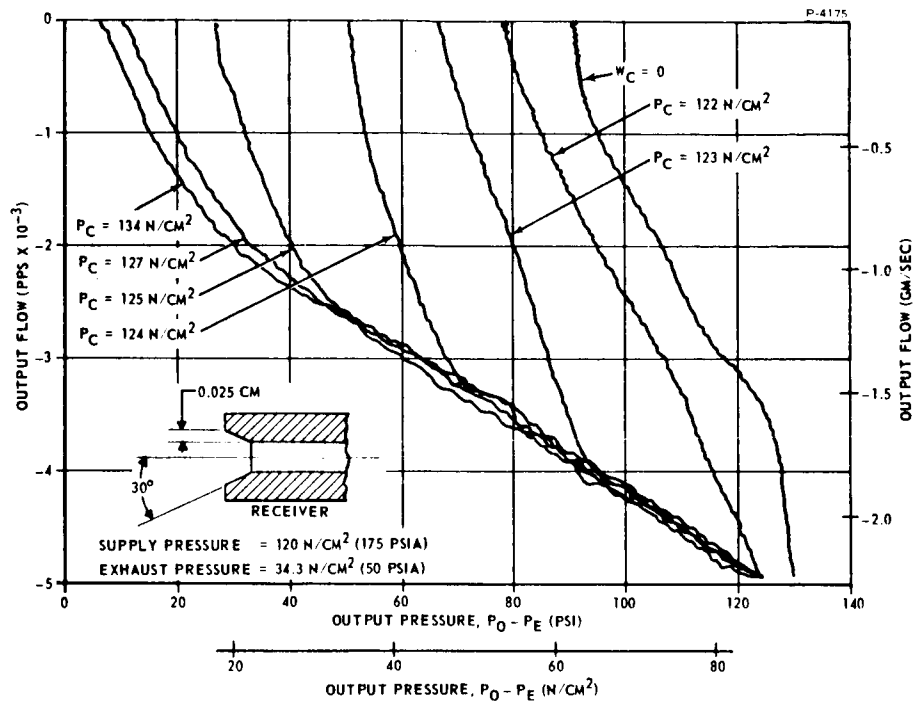


Figure 4-5 - Receiver Pressure - Flow Characteristics of Vortex Pressure Amplifier (Chamfered Receiver)

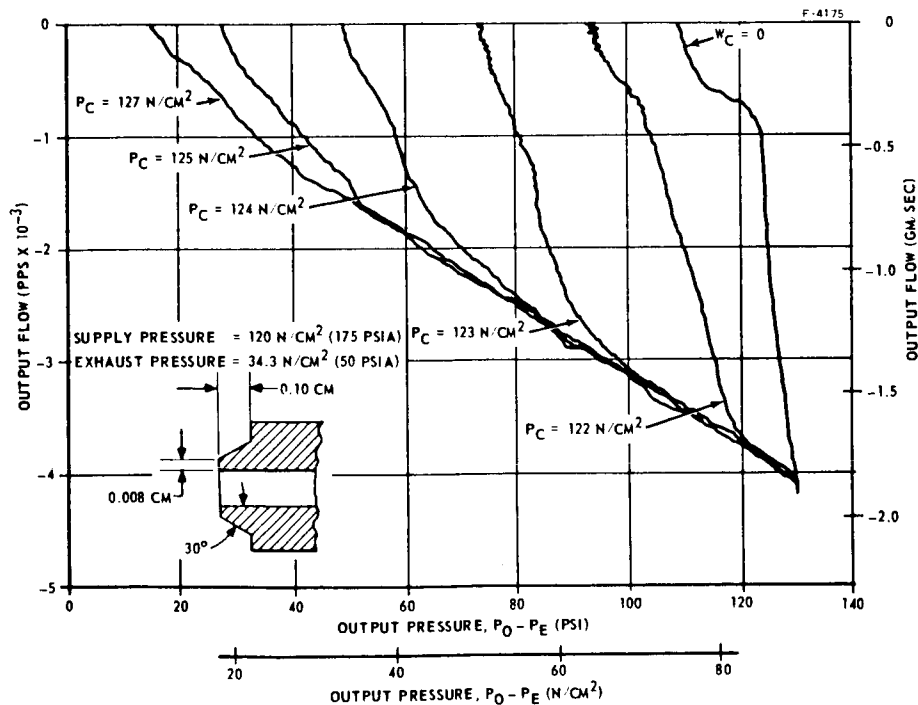


Figure 4-6 - Receiver Pressure - Flow Characteristics of Vortex Pressure Amplifier (Tapered Outer Edge)

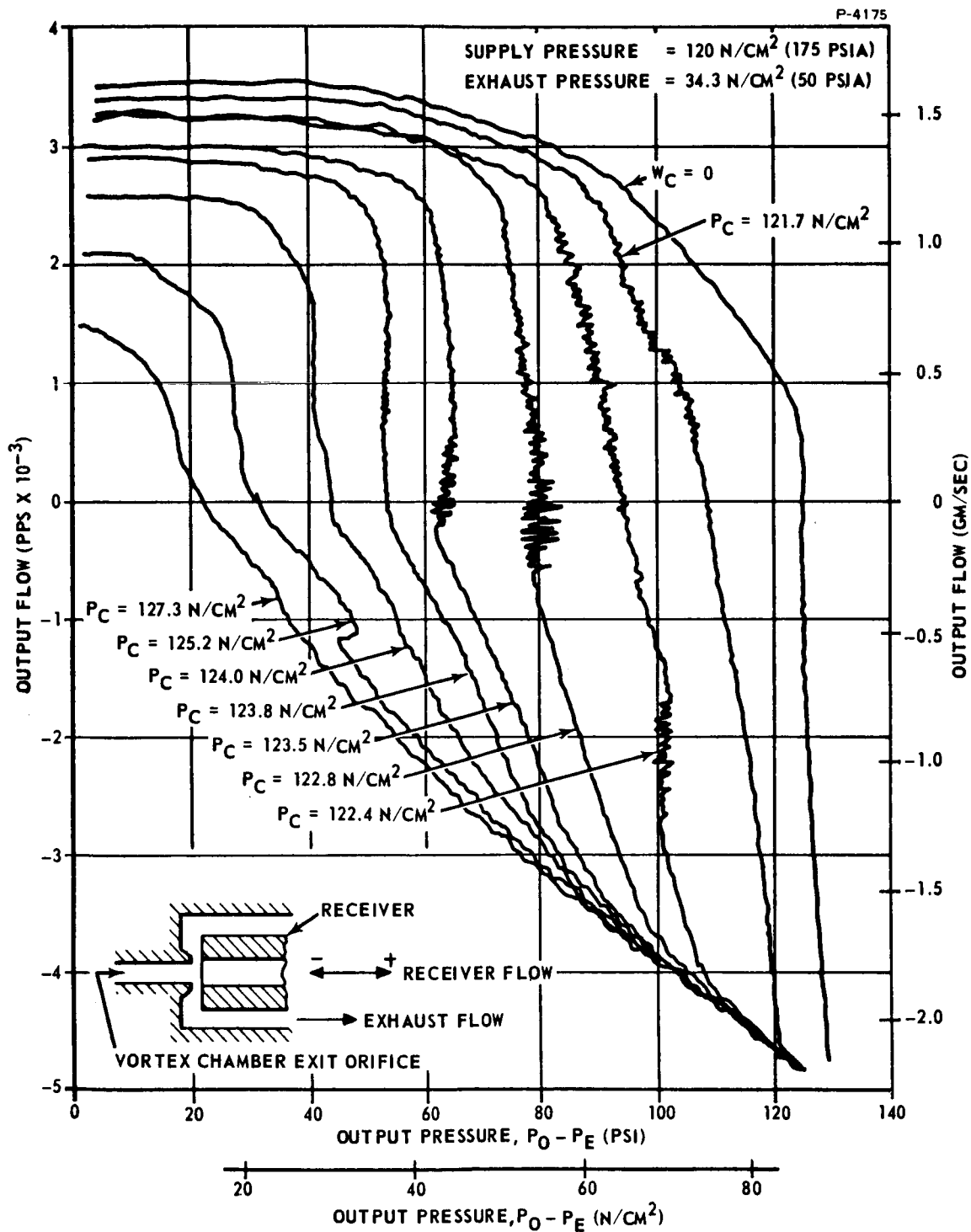


Figure 4-7 - Receiver Pressure-Flow Characteristics of Vortex Pressure Amplifier (Flat Faced Receiver and Undercut Chamber Exit)

seen that the maximum pressure at zero output flow was higher but the minimum pressure was also higher, so that the maximum pressure differential under blocked load condition was about the same. A small amount of negative resistance is evident and it can be seen from the pen trace that the output pressure was oscillatory in the negative resistance regions.

The above tests were performed with a single-exit vortex pressure amplifier. A dual-exit vortex pressure amplifier was tested also to determine whether there is any difference in the pressure-flow characteristics between a dual-exit and single-exit vortex pressure amplifier with the same receiver geometries. The pressure-flow characteristics of a dual-exit amplifier are shown in Figure 4-8. The configuration

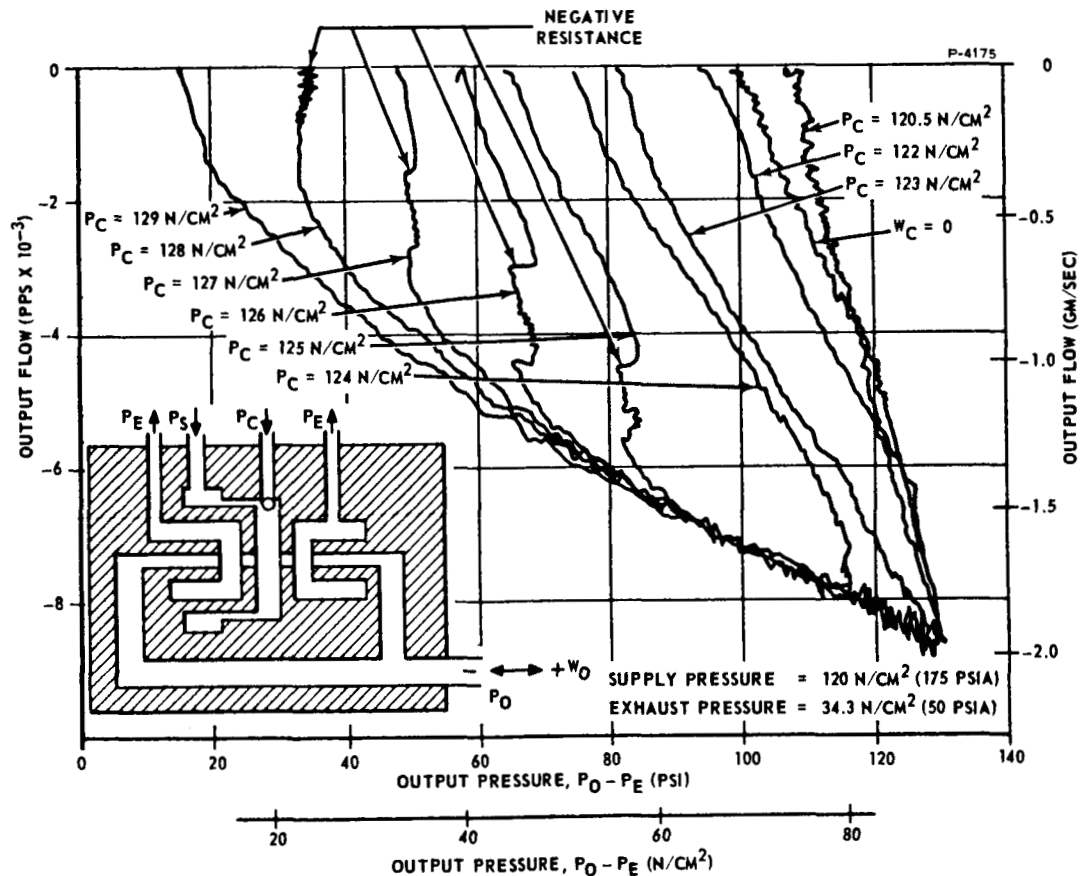


Figure 4-8 - Output Pressure-Flow Characteristics of Vortex Pressure Amplifier (Dual-Exit)

tested had flat-faced receivers identical to the configuration for which the test results were shown in Figure 4-4. The figure shows that the negative resistance is present, although there was no negative resistance in the single-exit configuration. The negative resistance is not as pronounced as that found in the original vortex pressure amplifier configuration but enough to cause oscillation of the output pressure.

Since the tests of the vortex pressure amplifier improved but did not eliminate the instability, it was decided to pursue the alternate servovalve design incorporating a vortex valve bridge power stage. Tests on this circuit are described in Section 5.

SECTION 5

VORTEX BRIDGE POWER STAGE

Tests were conducted on the vortex valve bridge power stage as a backup alternative to the vortex pressure amplifier. This power stage circuit utilizes four vortex valves connected in a bridge circuit rather than two vortex pressure amplifiers. A preliminary breadboard circuit representing one side of the power stage was assembled from existing vortex valves. The test data indicates that this type of circuit has stable, quiet output pressure characteristics. The pressure recovery was slightly low because the orifice sizes were not optimized. In order to evaluate this circuit more completely, a new vortex valve bridge power stage was designed, fabricated and tested. The pressure recovery of this configuration was about the same as that obtained with the vortex pressure amplifier power stage. The disadvantage of the four vortex bridge type of power stage is that it requires more control flow. The new power stage was not as stable as the preliminary breadboard circuit but was more stable than the vortex pressure amplifier power stage. Since the preliminary breadboard circuit was stable and quiet, it should be possible to stabilize the new power stage by proper sizing of the control and exit orifices. The new power stage tests were performed using a jet-on-jet proportional amplifier to control the power stage. The amplifier performance was satisfactory, and the tests proved the feasibility of using a jet-on-jet proportional amplifier in the pilot stage.

5.1 DESCRIPTION OF CIRCUIT

The new vortex valve bridge power stage consists of four vortex valves. A schematic of the circuit is shown in Figure 5-1. The control pressures to the power stage act in a push-pull manner. Each supply vortex valve has an exit orifice on each side of the vortex chamber. The exit orifices are not equal in diameter. The larger exit orifice is connected to one side of the load and to the supply port of an exhaust vortex valve on the same side of the load; the smaller exit orifice is connected to the control orifice of the same exhaust vortex valve.

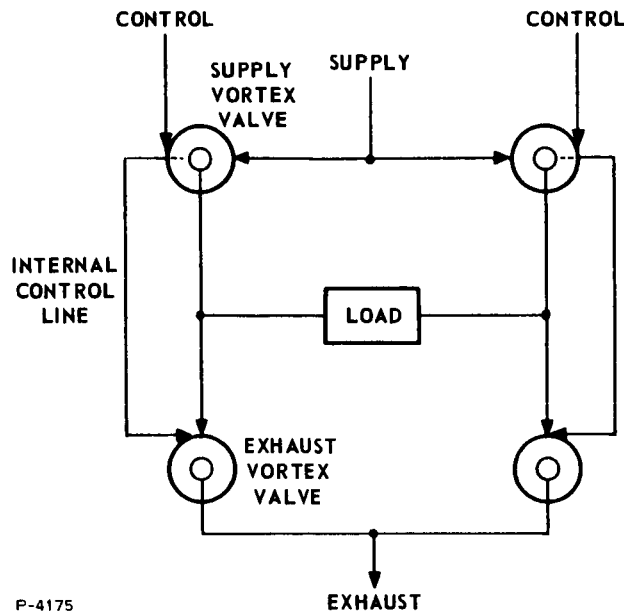


Figure 5-1 - Vortex Valve Bridge Power Stage

The principle of operation of the circuit is as follows: The supply and exhaust vortex valves operate out of phase such that when the supply vortex valve is "open" the exhaust valve is "closed" and vice-versa. When the maximum control flow is applied to the supply vortex valve, the supply flow is shut off and the control flow passes through the larger exit orifice to the supply port of the exhaust vortex valve. There is a radial pressure gradient in the vortex chamber of the supply vortex valve such that the pressure at the outer edge of the vortex chamber is equal to the supply pressure and decreases as the radius decreases. Therefore, since the internal exit has a smaller radius, the internal control pressure is lower than the load pressure, and thus the exhaust vortex valve receives no control flow and is in the "open" condition. The combination of "closed" supply valve and "open" exhaust valve results in a low load pressure. The opposite case occurs on the opposite side of the load, when the control flow to the supply vortex valve is zero and thus the supply valve is in the "open" condition. There is a pressure drop across the larger exit orifice because of flow through the orifice to the exhaust vortex valve. Because of this pressure drop, the internal control pressure is higher than the load pressure and control flow is introduced into the exhaust valve which tends to "close" it partly. The exhaust valve cannot shut off the flow completely because the load pressure would then be equal to the supply pressure and to the internal control

pressure, and no control flow could be introduced into the exhaust valve. The combination of "open" supply valve and partly "closed" exhaust valve results in a high load pressure.

5.2 PRELIMINARY BREADBOARD CIRCUIT TEST

The preliminary breadboard circuit consisted of two vortex valves representing one side or one half of the power stage. The circuit was assembled from existing valves. The orifice sizes, though not optimally matched, were thought to be close enough to determine feasibility of the circuit. Figure 5-2 shows a schematic of the circuit along with the control orifice and exit orifice diameters.

A schematic of the test setup used is shown in Figure 5-3. The flow was measured with a mass flowmeter transducer and the pressure was measured with a strain gauge type pressure transducer. The supply pressure to the circuit was set at 79.2 N/cm^2 (115 psia) and the exhaust pressure was one atmosphere. Output flow and output pressure data were taken at several control pressure levels in order to obtain a family of curves at constant control pressure levels.

The test data, shown in Figure 5-4, indicates that there is no negative resistance in the load pressure-flow characteristics. The pressure difference between the maximum and minimum output pressure at zero output flow is 45 N/cm^2 (66 psi), which is equivalent to 66 percent pressure recovery. No noisy or unstable areas were found.

The output pressure noise was measured by photographing the oscilloscope trace of the output pressure versus time. The data was taken with zero output flow and with a load volume of 82 cm^3 (5 in^3). The data are shown in Figure 5-5. The data taken indicate that the maximum noise is about 0.07 N/cm^2 (0.1 psi) peak-to-peak.

It was concluded from this test that the vortex bridge type of power stage appears feasible and has stable, quiet output pressure characteristics. The pressure recovery of this circuit was low, only 66 percent, but it was thought that this could be improved by optimizing the orifice sizes.

5.3 BREADBOARD VORTEX VALVE BRIDGE POWER STAGE TEST

A schematic of the vortex valve power stage is shown in Figure 5-6 along with sizes of the control orifices and chamber exit orifices.

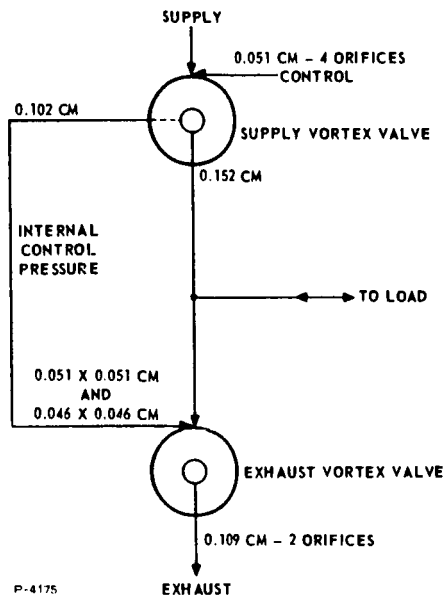


Figure 5-2 - Schematic of Preliminary Breadboard Vortex Valve Bridge Power Stage (One Side) Showing Orifice Diameters

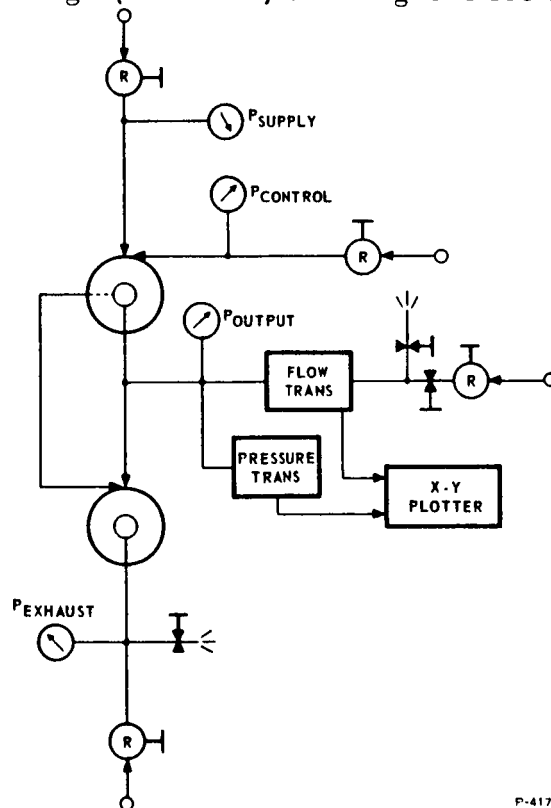


Figure 5-3 - Schematic of Vortex Valve Circuit Test Setup

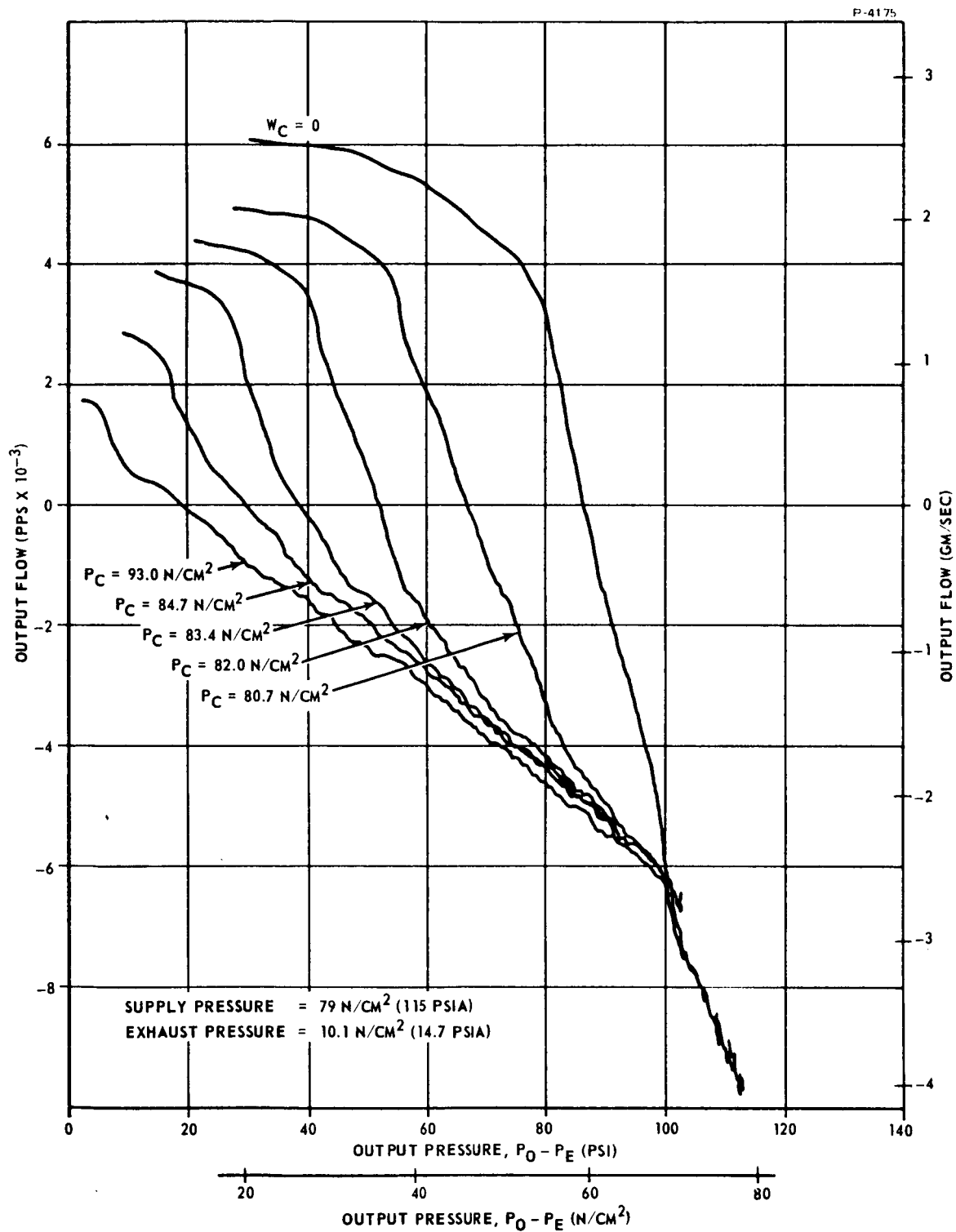


Figure 5-4 - Output Pressure-Flow Characteristics of Vortex Valve Circuit

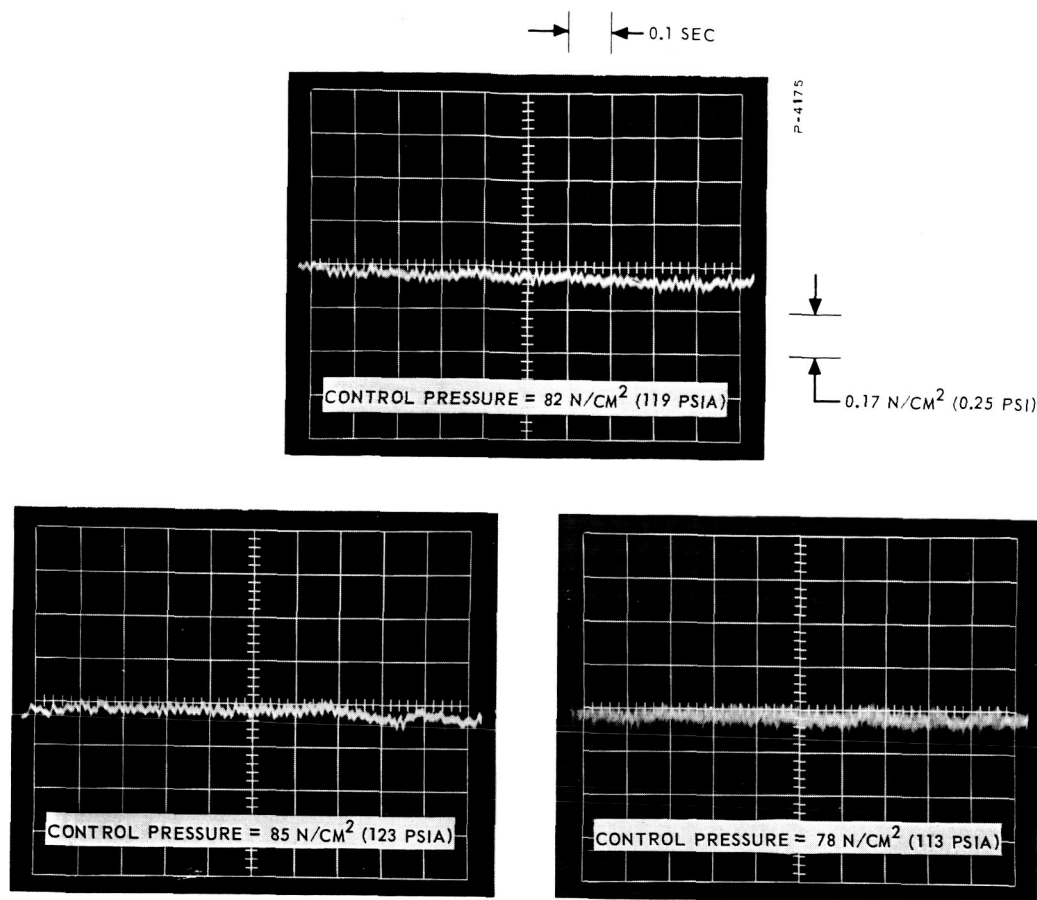


Figure 5-5 - Vortex Valve Circuit Noise

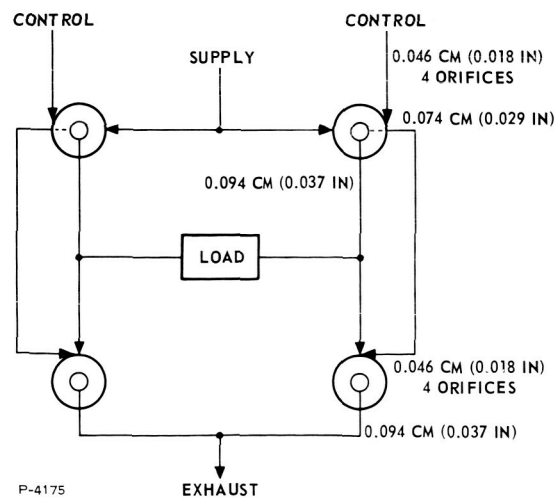


Figure 5-6 - Schematic of Breadboard Vortex Valve Bridge Power Stage Showing Orifice Diameters

First, one side of the valve was tested to determine whether any negative resistance characteristics were present in the output pressure flow characteristics and to determine the pressure recovery. The test setup used was the same as that shown in Figure 5-3. The supply pressure was 120.5 N/cm^2 (175 psia) and the exhaust pressure was 34.5 N/cm^2 (50 psia). Output flow versus output pressure data were taken at various values of constant control pressure. The test data are shown in Figure 5-7. The positive flow and reverse flow portions of the curves for control pressures of 124 N/cm^2 (180 psia) and 125 N/cm^2 (182 psia) do not meet at the zero output flow line, because the positive flow curves and reverse flow curves are run separately, and the control pressures are not always set exactly the same for the positive and reverse curves. The figure shows that the difference between the maximum and minimum output pressure at zero output flow is 71 N/cm^2 (103 psi). Negative resistance areas are not present although the slopes of the curves are almost vertical in several areas. However, the output pressure appears to be slightly noisy or oscillatory at low positive output flows for $P_c = 122 \text{ N/cm}^2$ (177 psia) and $P_c = 125 \text{ N/cm}^2$ (182 psia). Figure 5-8 shows a photograph of the oscilloscope trace of the output pressure versus time. The photo was taken with zero output flow and with the control pressure at 125 N/cm^2 (182 psia). The oscillation consists of a triangular-shaped wave at a frequency of 10 hertz and amplitude of 1.03 N/cm^2 (1.5 psi) peak-to-peak.

Tests were also performed on the complete vortex bridge power stage. A schematic of the test setup is shown in Figure 5-9. The power stage was controlled by a pilot stage consisting of a jet-on-jet proportional amplifier and an ejector. The supply pressure to the pilot stage was 148 N/cm^2 (215 psia), and the exhaust pressure of the power stage was 34.5 N/cm^2 (50 psia). The performance of the amplifier and ejector were satisfactory. The output flow versus output pressure characteristics are shown in Figure 5-10. The data indicate that the maximum load flow is 1.41 gm/sec (0.0031 lb/sec) and the maximum differential output pressure is 69.7 N/cm^2 (101 psi). Negative resistance areas and unsteady output pressures are evident in the reverse pressure and flow quadrant. The output pressure noise was measured and a 9 hertz, 6.9 N/cm^2 (10 psi) peak-to-peak oscillation was found at about zero differential pressure.

The source of the output pressure oscillation can be traced back to the pressure-flow characteristics of one side of the power stage which were shown in Figure 5-7. The slopes of the curves near the zero flow line are very steep so that there is little or no stability margin.

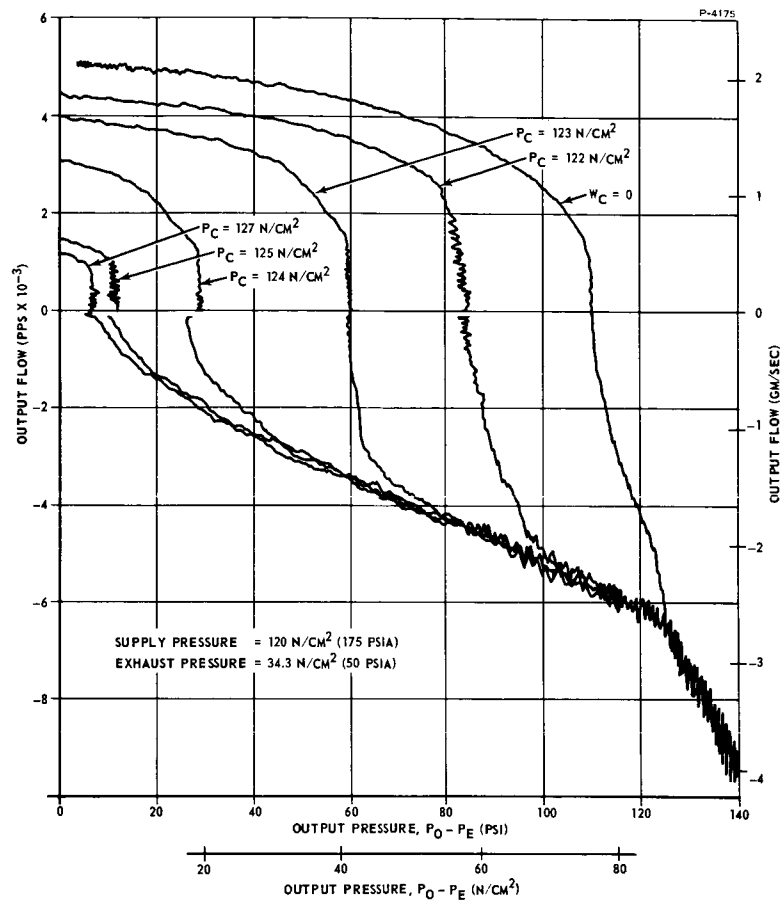


Figure 5-7 - Output Pressure-Flow Characteristic of One Side of Breadboard Vortex Valve Bridge Power Stage

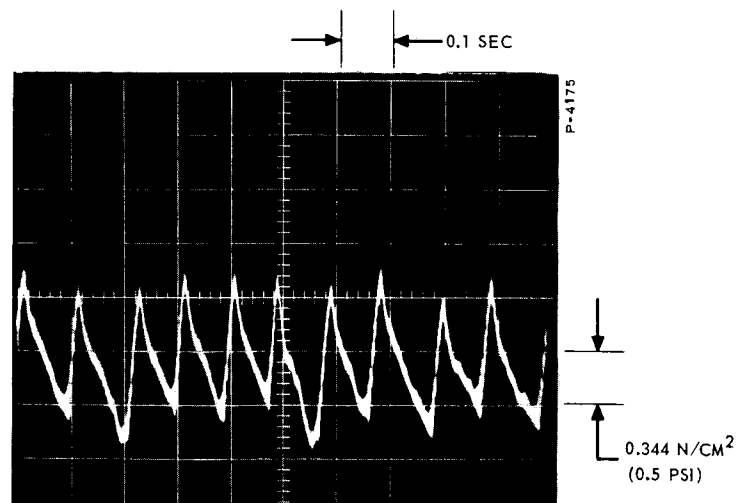


Figure 5-8 - Output Pressure Stability of One Side of Breadboard Vortex Valve Bridge Power Stage

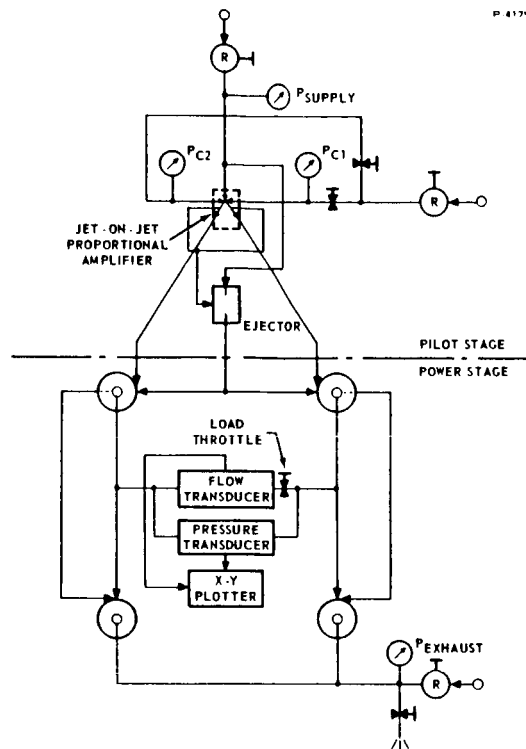


Figure 5-9 - Schematic of Vortex Valve Bridge Power Stage Test Setup

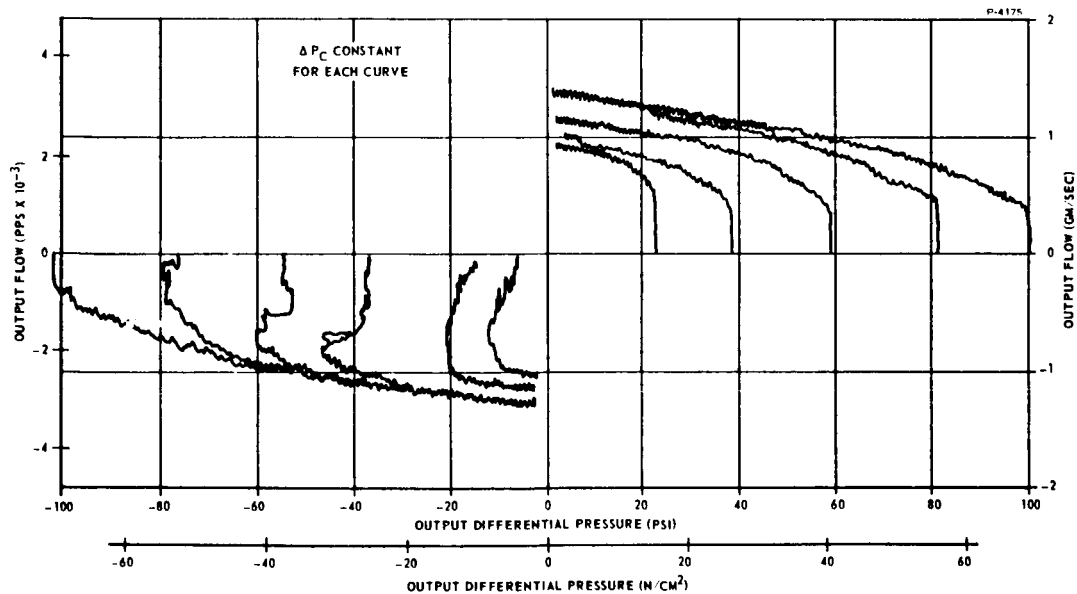


Figure 5-10 - Output Pressure Versus Output Flow Characteristics of Vortex Valve Bridge Power Stage

The power stage would be stable if the sides of the power stage had pressure-flow characteristics with slopes near the zero flow line similar to those of the preliminary breadboard shown in Figure 5-4. The slopes of the pressure-flow curves will be made less steep by decreasing the control area of the exhaust vortex valves or by decreasing the size of the smaller exit orifice in the supply vortex valve.

The following conclusions were made from the test results of the vortex bridge power stage:

- (1) The pressure recovery of the vortex valve bridge power stage is about the same as that of the vortex amplifier power stage.
- (2) The stability of the vortex valve bridge power stage should be superior to the vortex pressure amplifier power stage.
- (3) The control flow required by the vortex valve bridge power stage is about double that of the vortex pressure amplifier power stage.

SECTION 6
GOALS FOR NEXT PERIOD

The next quarter goals will be to:

- (1) Improve the stability of the vortex valve bridge power stage by modifying the control and exit orifice sizes.
- (2) Test the servovalve with the addition of Venjet amplifiers and summing vortex valves.
- (3) Conduct acceptance tests of the breadboard servovalve.
- (4) Begin the design of the prototype servovalve.

APPENDIX A

DESIGN SPECIFICATIONS FOR FLUERIC SERVOVALVE

1. SCOPE

The specification covers a valve to be designed to meet the requirements of NASA Contract Number NAS 3-7980, entitled "Design, Fabrication and Test of a Flueric Servovalve."

2. DESCRIPTION

The servovalve shall be a four-way valve with dynamic negative feedback of the output pressure. The servovalve shall contain no moving mechanical parts such as bellows, variable orifices, and jet-pipes. The principle of operation shall be the interaction of fluid streams.

3. SUPPLY AND EXHAUST SPECIFICATIONS

3.1 Phase 1 - Breadboard Model

3.1.1 Working Fluid: The working fluid shall be both nitrogen and hydrogen gas.

3.1.2 Temperature: Supply gas shall be room temperature.

3.1.3 Supply Pressure: The supply pressure shall be 148 ± 7 newtons per square centimeter, absolute (215 ± 10 psia).

3.1.4 Exhaust Pressure: The exhaust pressure shall be 34.5 ± 3.5 N/cm²a (50 ± 5 psia).

3.1.5 Supply Flow: Under all operating conditions, the flow through the supply port shall be less than 1.82 times the rated no-load output flow, where "rated no-load output flow" is defined here as the mass flow through the wide open load-throttle for rated input-signal. "Rated input-signal" is defined in Paragraph 5.2.

3.2 Phase II - Breadboard Model and Prototype Servovalve

- 3.2.1 Working Fluid: The working fluid shall be dry hydrogen.
- 3.2.2 Temperature: Supply gas temperature shall be variable from 56 to 333 degrees Kelvin (100 to 600°R).
- 3.2.3 Supply Pressure: The supply pressure shall be 148 ± 7 N/cm²a (215 ± 5 psia).
- 3.2.4 Exhaust Pressure: The exhaust pressure shall be 34.5 ± 3.5 N/cm²a (50 ± 5 psia).
- 3.2.5 Supply Flow: Under all operating conditions, the flow through the supply port shall be less than 1.82 times the rated no-load output flow.

4. LOAD SPECIFICATION

The two output ports shall be connected to a load consisting of a series arrangement of a volume-throttle-volume combination. The load shall contain no vents. The load volumes shall be adjustable to the extent that the difference between the two volumes can vary between plus and minus 115 cubic centimeters (7 in³). The total of the two volumes shall remain equal to 164 cm³ (10 in³). The load-throttle shall be a two-way valve adjustable from closed to wide open passageway. With wide open load throttle, the differential output pressure shall be less than 5 N/cm² (7 psi).

5. INPUT-SIGNAL SPECIFICATIONS

5.1 Input-Signal: The input-signal shall be a two-port differential pneumatic signal. The working fluid shall be the same as the supply gas for the servovalve. "Input-signal pressure" is defined here as the pressure difference between the two input ports.

5.2 Rated Pressure: The rated input-signal pressure shall be less than 7 N/cm² (10.2 psi) for flow in both directions through the load-throttle. "Rated input-signal" is defined here as the input-signal that produces the rated no-load flow specified in Paragraph 6.2.

5.3 Quiescent Pressure: For zero input-signal, the pressure bias of the input-signal shall be less than $45 \text{ N/cm}^2\text{a}$ (65.3 psia); where "pressure bias" is defined here as the average pressure of two lines.

5.4 Admittance: Variation in the admittance of each input port, resulting from changes in the load-throttle, shall be less than 10 percent of the maximum input admittance for the complete range from closed to wide open load-throttle; where "admittance" is defined here as the mathematical derivative of volumetric flow with respect to the absolute pressure in the input port. No specification is placed upon variation in the input admittance as a function of the input-signal.

5.5 Power: Under all operating conditions with dry hydrogen at 56°K (100°R), the combined power delivered to the input ports shall be less than 4 watts; where "power" is defined here as the product of the gage pressure (i.e., pressure relative to the exhaust pressure) and volumetric flow.

6. OUTPUT SPECIFICATIONS

6.1 Output: The servovalve shall have two output ports. "Differential output pressure" is defined here as the pressure difference between the output ports. "Output flow" is defined here as the mass flow through the load-throttle.

6.2 Rated No-Load Flow: With wide open load-throttle, the output flow of dry hydrogen at 56°K (100°R) shall be 2.1 grams per second (0.00463 lb/sec) for the rated input-signal..

6.3 Pressure Recovery: With closed load-throttle, the differential output pressure shall be greater than 82 N/cm^2 (119 psi); i.e., 73 percent pressure recovery.

6.4 Pressure-Flow Characteristics: For all values of constant input-signal, the output flow shall be equal to or greater than

$$\dot{m}_o \left(1 - \frac{p}{p_o} \right)$$

where quantity \dot{m}_o is a constant and equals the output flow for the given input-signal with closed load-throttle; p_o is a constant and equals the

differential output pressure for the given input-signal with closed load-throttle; and p is a variable term equal to the differential output pressure for the given input-signal and is a function of the load-throttle setting.

6.5 Linearity: Deviation from a straight line of input-signal pressure versus differential output pressure for closed load-throttle shall be less than 10 percent of the rated values. The pressure gain for all values of input-signal shall be less than two (2) times the average pressure gain, where "pressure gain" is defined here as the mathematical derivative of the differential output pressure with respect to the input-signal pressure during steady operating conditions with closed load-throttle.

6.6 Pressure Feedback: Dynamic negative feedback of the pressure of each output port shall be an integral part of the servovalve. The feedback gain at zero frequency shall be less than 1 percent of the rated input-signal. The feedback gain at the corner (break) frequency of 5 hertz shall be 8 ± 1 percent of the rated input-signal. Construction of the servovalve shall allow easy exchange of components for changing the pressure feedback characteristics.

6.7 Stability: Peak-to-peak ripple of frequencies above 3 hertz shall be less than 0.4 N/cm^2 (0.58 psi) measured after filtering an electrical signal of the differential output pressure with a $1/(0.05S + 1)^2$ filter, for various load-volume settings and for all values of input-signal with closed load-throttle.

6.8 Transient Response: From any initial value and for step input-signals that produce a 20 N/cm^2 (29 psi) change in the differential output pressure, the differential output pressure shall reach 62.5 percent of the step in a time period of less than 0.055 second and shall settle within 2 N/cm^2 (2.9 psi) of the final value in a time period of less than 0.210 second when tested with closed load-throttle and with equal load-volumes.

6.9 Frequency Response: With zero load-volumes and blocked output ports, the phase shift of the differential output pressure for a 2 percent rated input-signal at 6 hertz shall be less than 20 degrees, and at 60 hertz the phase shift shall be less than 90 degrees. The differential output pressure amplitude variation for a constant input-signal shall be less than ± 2 db from 0 to 60 hertz.

6.10 Threshold: For all values of input-signal, the increment of input-signal required to produce a change in the output shall be less than 0.5 percent of the rated input-signal.

6.11 Hysteresis: The difference in the input-signal required to produce the same output during a single input cycle shall be less than 3 percent of the rated input-signal.

7. ENVIRONMENT SPECIFICATIONS

Items 7.2, 7.3, and 7.4 shall not apply to the breadboard model of the servovalve.

7.1 Ambient Temperature: The servovalve shall be capable of operation under ambient temperatures that vary between 56 and 333°K (100 and 600°R).

7.2 Vibration: The servovalve shall be operational when subjected to 6 g's amplitude from 0 to 20 hertz and then linear amplitude to 20 g's at 200 hertz and then constant at 20 g's to 2000 hertz along any axis.

7.3 Shock and Acceleration: The servovalve shall operate after a 6-g shock and/or an 8-g acceleration along any axis.

7.4 Radiation Field: The servovalve shall be operational under a total dose of 6×10^6 rads (ethylene) 1 hour; a fast neutron flux rate ($E > 1.0$ mev) of 3×10^{11} neutrons/cm²-sec; a thermal neutron flux ($E < 1.86$ EV) of 1×10^{10} neutrons/cm²-sec; and a gamma heating equivalent to 770 watts/kilogram aluminum (350 watts/lbm aluminum).

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